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13. ABSTRACT *(Maximum 200 words)*
This study developed an algorithm to estimate TDEE using pedometry. Sailors (7 men, 10 women were studied for 8 d at sea using doubly labeled water (DLW) to estimate TDEE. Concomitantly, pedometry was used to measure foot-ground contact times during running (RCON) and walking (WCON), and the fraction of time spent running (RUN), walking (WALK), or in other (OTHER) forms of foot movement. Resting metabololic rate (RMR) was estimated from body mass (BM), sex, age, lean BM. The predictive model is a variation of a previously developed model (JAP 76:1818-22, 1994), where TDEE = 1440* [RUN*((0.0761*[BM/RCON])-7.598) + WALK* ((0.056* [BM/WCON])-2.938)+(OTHER*0.1*RMR)+RMR]. This equation explained 79% of the variance relative to DLW TDEE. TDEE (Mean ± SEM: 3023 ± 99kcal/d) predicted by pedometry (95% confidence ± 193 kcal/d) did not suffer from TDEE by DLW (3000 153 kcal/d). The abundance of ramps and ladders on ships increased vertical locomotion components relative to horizontal, which normally predominate on land, possibly limiting the ability of pedometry to classify shipboard activity. However, TDEE was predicted with reasonable accuracy using estimated RMR and this pedometry method.

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PREDICTION OF TOTAL ENERGY EXPENDITURE USING A PEDOMETER IN MALE
AND FEMALE SAILORS ABOARD SHIP

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EXECUTIVE SUMMARY

The primary purpose of this study was to evaluate the accuracy of a newly developed equation to estimate total energy expenditure (TEE) from pedometry data. The doubly labeled water (DLW) method was used to measure average daily TEE of U.S. Navy sailors (9 men, 16 women) for 8 days while aboard ship at sea. Men expended significantly more energy than women (3446 $\pm$ 215 kcal/day vs. 2776 $\pm$ 166 kcal/day) largely attributable to the men weighing more and having a greater lean body mass (LBM). There was no difference in measured TEE between jobs classified by the Navy (16,24) as having high physical demands versus those with low physical demands. Pedometers worn during the 8-day TEE assessment measured (a) foot-ground contact times during running, walking, and other forms of slow foot movement such as shuffling and foot tapping, and (b) the proportion of time spent in each of these forms of locomotion. Resting metabolic rate (RMR) was estimated from LBM (2). The equation differentiates differences in foot-ground contact times based on mode of activity (e.g., run, walk, other slow foot movements and no activity). The new equation is:

Total Energy Expenditure = 1440 * [Percent Run Time * ((0.0761 * [Body Mass/Contact Time During Running]) - 7.598) + Percent Walk Time * ((0.056 * [Body Mass/Walk Contact Time]) - 2.938) + (Percent Other Slow Foot Movement Time * 0.1 * Resting Metabolic Rate/Minute)] + Resting Metabolic Rate.

This equation explained 79% of the variance of pedometer-predicted TEE relative to TEE assessed by DLW with a 95% confidence interval of $\pm$ 193 kcal/day. Mean TEE predicted by foot pedometers of 3023 $\pm$ 99 kcal/day (Mean $\pm$ SEM) did not differ from mean TEE assessed by DLW of 3000 $\pm$ 153 kcal/day. The equation did not predict with sufficient accuracy TEEs over 4000 kcal/day. One possible explanation for the lack of precision is the variability in the way the data is stored. Small errors in the proportion of time spent in each activity become additive over 8 days, impacting the accuracy of the equation. The unique environment of the ship, with its abundance of ramps and ladders, may limit the accuracy of this equation to other warfighters with land-based missions. Since TEE associated with various military operations are not entirely known, and the daily minute-to-minute pattern of energy expenditure in military operation training is not known, further work on pedometry appears justified.

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INTRODUCTION

Accurate assessment of total energy expenditure (TEE) in free-living humans is difficult (14). The doubly labeled water (DLW) method to measure TEE in humans (20), provides a reliable and accurate way to assess TEE, but it is expensive. A considerably cheaper alternative to DLW to measure TEE is the pedometer. Human activity has been measured with pedometers (through counting steps or calculating distances covered) for over 500 years (14). Pedometers were not originally designed to quantitatively assess energy expenditure (EE), but recently manufacturers have claimed their devices can accurately determine EE of activity (14). Studies have shown that conventional pedometers can predict actual EE with correlation coefficients ranging from r = 0.46 to 0.88 during controlled laboratory studies, but few studies have assessed the validity of pedometer estimates of EE in field environments (23). Three studies have compared pedometer EE measurements to those made by DLW in free-living environments. One study showed a significant correlation (r = 0.61; $p < 0.002$) between the EE derived from pedometry measurements obtained using the Caltrac (Muscle Dynamic Fitness Network, Torrence, CA) pedometer and algorithm and EE derived using DLW in elderly patients with restricted (intermittent limping) ambulatory movement (7). However, non-significant relationships were reported between pedometer and DLW assessed EE in the other two studies, one with overweight women (6) and the other with young healthy adult women (12). All three of these studies used different pedometers and attempted different prediction equations based on pedometer counts and body mass. Recently, Hoyt et al., (9) demonstrated that by knowing total weight of a volunteer, i.e., body weight plus clothing and other gear carried, a specially designed foot-ground contact monitor could accurately predict ($R^2 = 0.93$) exercise EE of men walking and running on a treadmill.

The primary purpose of the present study was to determine if a foot-ground contact pedometer (Fitsense Technology, Inc., Wellesley, MA) could provide an accurate estimate of TEE using a newly developed algorithm. An additional aim was to assess TEE of male and female sailors doing their normal jobs aboard ship at sea to determine if TEE differed by gender or job classification.

METHODS

VOLUNTEERS

Twenty-eight U.S. Navy sailors (10 men and 18 women), crewmembers assigned to an amphibious assault ship that resembled a small aircraft carrier, volunteered to participate in this study. Three sailors (1 man and 2 women) served as controls for the DLW procedure to assess effects of changes in background isotope levels associated with changes in the dietary water source and therefore do not have TEE data. The institution's scientific and human use committees approved the study. Prior to data collection all 28 volunteers were briefed on the study and gave their written consent. Of the 25 test volunteers receiving DLW, complete TEE and foot pedometer data sets were

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only obtained from 7 men and 10 women. The other 8 volunteers had malfunctions with the pedometers or the pedometer could not be securely attached to the style of shoe or boot they wore. Those volunteers that had complete DLW measurements were used to classify TEE by gender and job type. Volunteers were participating in a routine 8-day field training exercise (FTX) at sea. Participants had a variety of jobs classified by the Navy (16,24) for physical demand as high (5 men and 10 women) or as low (4 men and 6 women). Physical demand classifications were based on ratings from subject matter experts who rated 73 different Navy jobs for the strength, flexibility, body balance, and stamina required using 5-point scales (not very important to extremely important). The ratings for these 4 categories were averaged to reflect total physical demand of the job (16,24). For this study, jobs with ratings greater than 3.0 were classified as high physical demand and those with ratings less than 2.0 were classified as low physical demand. No volunteers had jobs with a physical demand for their job between 2.0 and 3.0.

EXPERIMENTAL DESIGN

Volunteers were instrumented with the pedometers on Day 0 of the study at the same time they received the DLW for TEE measurement. Body weights were obtained from volunteers in t-shirts and underwear prior to the administration of the DLW (Day 0) and at the conclusion of the study (Day 8). Age and height were also recorded on Day 0.

Methods to assess TEE using DLW are previously described (4). Briefly, on Day 0 volunteers refrained from eating or drinking for approximately 6 hrs, and then provided an ~ 30 ml urine sample and ~ 10 ml of saliva. Volunteers then consumed ~ 0.25 g/kg of total body water (TBW) of $H_2^{18}O$ and 0.18 g/kg of TBW of ^2H_2O (Isotec Inc., Miamisburg, OH), or tap water (controls). Total body water was estimated as 73% of lean body mass (LBM) (20). Lean body mass was estimated to be 15% of body weight for men and 25% of body weight for women (5,13). About 50 ml of the ship's drinking water was also consumed after it was used to rinse the dose container. Saliva samples (~ 10 ml) were collected at 3 hr and 4 hr post-DLW ingestion for TBW determinations (10,20).

First morning urine samples were collected on each morning for the 8 days of the study to measure isotope elimination rates for ^2H and ^{18}O. Background changes in baseline isotopic abundances due to a changed water source were measured in 3 volunteers who were given tap water rather than the labeled water. This allowed for greater precision in the estimate of TEE than if these corrections were not done (4). Estimated TEE was obtained from the rate of CO_2 production calculated through analysis of differential isotope elimination rates using methods previously described (4). A metabolic fuel quotient of 0.85 was assumed based on typical western diets with body fat reserves remaining stable (14). Body energy stores were calculated by isotope dilution ($H_2^{18}O$) measurements of TBW (10). Fat-free mass was calculated as the difference between body mass and fat-free mass. Fat-free mass was assumed to be

27% protein and 73% water; fat mass was assumed to be 100% fat. Energy equivalents of 4.4 kcal/g for protein and 9.5 kcal/g for fat were used (10).

Foot pedometer estimates exercise EE based on total weight (body and clothing weight) and contact time of the foot with the ground as measured by the accelerometers and a microprocessor within the pedometer (9). This approach is based on the relationship that EE generated during walking or running is primarily determined by the cost of supporting one's body weight and the rate at which this locomotion force is generated (11,21).

The foot-ground contact pedometer (Fitsense Technology Inc., Wellesley, MA) (Figure 1) is a small electronic device (approximately 5.8 cm x 7.6 cm x 6.4 cm; 56 g) that fits into a cloth pouch mounted to the outside of the boot or shoe through the shoelaces. Encased within the monitor are an accelerometric sensor circuit, an analog to digital converter, and a microcontroller (microprocessor, memory, real time clock, and computer interface unit). The pedometer collects information on each step and records contact time in milliseconds. The memory can hold 81,760 samples of data. Data is transferred from the pedometer to a laptop computer using a manufacturer designed wire interface unit and manufacturer supplied software (Logger Interface v 2.19; Fitsense Technology Inc., Wellesley, MA). This software also identifies the different types of foot movement activity. Briefly, the pedometer provided a step-by-step estimate of foot-ground contact time. The algorithm identifies the accelerometric signal associated with heel impact and toe off that is generated within the sensors of the pedometer during each stride to identify the specific foot-ground contact times to within $\pm$ 2 ms (25). Activity classifications of run, walk, other slow foot movements, and no activity are determined by the pattern of the foot-ground contact waveforms. The pedometer measures foot-ground contact time by identifying the rapid foot de-acceleration on heel strike, and the more subtle acceleration on toe-off. Periods of no acceleration are classified as "no activity". Periods of walk and run were differentiated by the duration of foot-ground contact time, with foot-ground contact time of 500 msec or less classified as run and over 500 msec classified as walk (Buller and Weyand, unpublished data). Other slow movement periods were classified when a heel strike was detected but the subtler toe-off signal was not. These other slow movements generally occur when movement velocity was less than 0.9 m/sec (25).

Volunteers were instructed to wear the pedometers on their shoes during the entire FTX. If participants changed shoes, for example putting on athletic shoes to go to the gym, they were instructed to move the pedometer to the pair of shoes they were wearing. Pedometer data was downloaded and batteries changed on Day 5. Pedometers were returned to participants within 30 minutes. Pedometer data was also downloaded at the conclusion of the FTX on Day 8.

Figure 1. AMS-2 foot-ground contact pedometer (Fitsense Technology, Inc., Wellesley, MA).
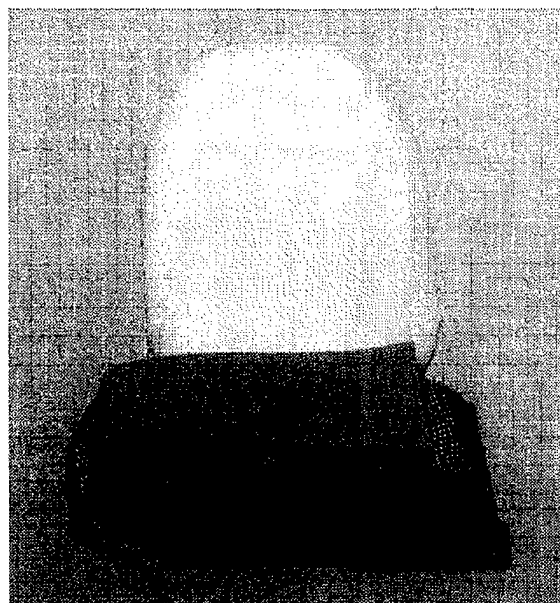
DATA ANALYSIS

Descriptive statistics are reported as means ± standard errors of the mean (SEM). Analyses of variance were used to determine mean differences in TEE by gender, job classification, and assessment type (DLW vs. pedometer). Analyses of covariance with body weight and LBM as covariates were used to determine how gender differences in TEE were influenced by these covariates.

Each volunteer had two pedometer data files (Day 0 to Day 5, and Day 5 to Day 8). Pedometer data files were merged to have a continuous data file minus the 30 minutes not recorded when batteries were changed and files downloaded on Day 5. The amount of time spent in each activity (run, walk, other slow movements, and no activity) was summarized. Average foot-ground contact times for each of these modes of activity were calculated. Predictive equations used activity recorded in these four modes of activity. Total energy expenditure is composed of active EE and resting metabolic rate (RMR). Resting metabolic rate was estimated from LBM using a previously validated model, where:

(Equation 1): RMR (kcal/day) = 500 + 22 (LBM) (2).

The prediction equation used an adaptation of a previously developed model from Hoyt et al. (9) and equations developed from unpublished data (Buller and

Weyand; Buller and Santee). The concept determines the proportion of time spent in each activity (run, walk, etc.) and then determines TEE by adding the various EEs of each activity. Energy of each activity is determined by multiplying the amount of time spent in that activity by the rate of EE of that particular activity (15). Using multiple regression, the original equation from Hoyt et al. (9), determined the EE of volunteers while exercising on a treadmill while wearing a specially designed force-sensitive insole. That equation is:

(Equation 2): Energy Expenditure in Watts, $(EE(W)) = 3.701 * (Total Body Weight/ Contact Time With the Ground)$.

However, walking and running foot-ground contact patterns were not differentiated using the original equation (9). This original equation was modified in a second study of 14 volunteers running and walking on a treadmill (25). These equations were modified as a result of a new pedometer (i.e., the same pedometer that was used on this study) being used that had manufactured supplied algorithms to identify differences in walking and running rates. Significant regression equations were developed to determine the individual EE for each activity. These equations were:

(Equation 3): Energy expenditure of running, $EE_{run}(W) = 4.517 * (Total Body Weight/ Contact Time With the Ground) - 378.33$ ($R^2 = 0.76$, $p < 0.001$) (Buller and Weyand, unpublished data).

and

(Equation 4): Energy expenditure for walking, $EE_{walk}(W) = 4.312 * (Total Body Weight/ Contact Time With the Ground) - 269.62$ ($R^2 = 0.56$, $p < 0.001$) (Buller and Weyand, unpublished data).

These equations were then validated ($R^2 = 0.89$, $p < 0.001$) (Buller and Santee, unpublished data) from data of a larger study of volunteers walking and running 1300 m to 1600 m on a dirt road with loads of 13.6 kg or 27.3 kg or without a load (18,19). The new predictive equation for the present study used these equations and estimates for other slow foot movements and RMR.

RESULTS

Physical characteristics of the volunteers by gender are shown in Table 1. Men expended more energy than women ($p < 0.03$), but when body weight or LBM were used as covariates, there was no significant gender difference (Figure 2). There was also no significant difference in TEE by job type (Figure 3).

Table 1. Physical characteristics (mean ± SEM) by gender.

	Men (n = 9)	Women (n=16)	All (n=25)	Significance
Age (yrs)	24 ± 1	25 ± 1	25 ± 1	NS
Height (cm)	177 ± 9	164 ± 9	169 ± 2	0.001
Pre-FTX Weight (kg)	79.1 ± 3.9	68.1 ± 3.5	72.4 ± 2.8	0.05
Post-FTX Weight (kg)	79.2 ± 3.9	67.4 ± 3.4	72.1 ± 2.7	0.05
Lean Body Mass (kg)	65.9 ± 3.0	44.4 ± 6.6	53.0 ± 2.6	0.001
Body Fat (% of Body Weight)	18.0 ± 7.2	31.5 ± 1.8	26.1 ± 1.9	0.001
Body Mass Index (kg/m^2)	24.6 ± 1.0	24.9 ± 1.2	24.8 ± 0.8	NS

A summary of the amount and proportion of activity by gender and job classification are shown in Tables 2 and 3 respectively. The new predictive equation developed for the present study used the same walking and running components described above but converted values into kilocalories per minute. The energy cost of slow foot movements was estimated as 0.1 * RMR/minute based on the following rationale. The energy cost of standing quietly is approximately 12% to 22% above RMR. However, foot movements can occur while lying down or sitting, with estimates of energy cost in these positions only 0% to 10% above RMR (1). Therefore, a value of 0.1 times RMR per minute was chosen as the value to account for slow foot movements. A constant, 1440 (number of minutes in a day), was multiplied to obtain 24 hr TEE. RMR was added to account for resting energy expenditure. This new prediction equation, explained 79% of the variance. The slope of the regression line is 0.61 with the line of identity slope equal to 1.00. The predictive equation is:

(Equation 5): **TEE (kcal) = 1440 * [Percent of Time Spent Running * ((0.0761) * [Body Mass / Contact Times During Running]) - 7.598) + Percent of Time Spent Walking * ((0.056) * [Body Mass / Contact Times During Walking]) - 2.938) + Percent of Time Spent Doing Other Slow Foot Movements * (0.1 * Resting Metabolic Rate/Minute)] + Resting Metabolic Rate.**

This equation predicts with 95% confidence TEE within ± 193 kcal/day. Individual pedometer predicted TEE plotted against DLW TEE is shown in Figure 4. There was no significant difference in mean TEE by method (Figure 5).

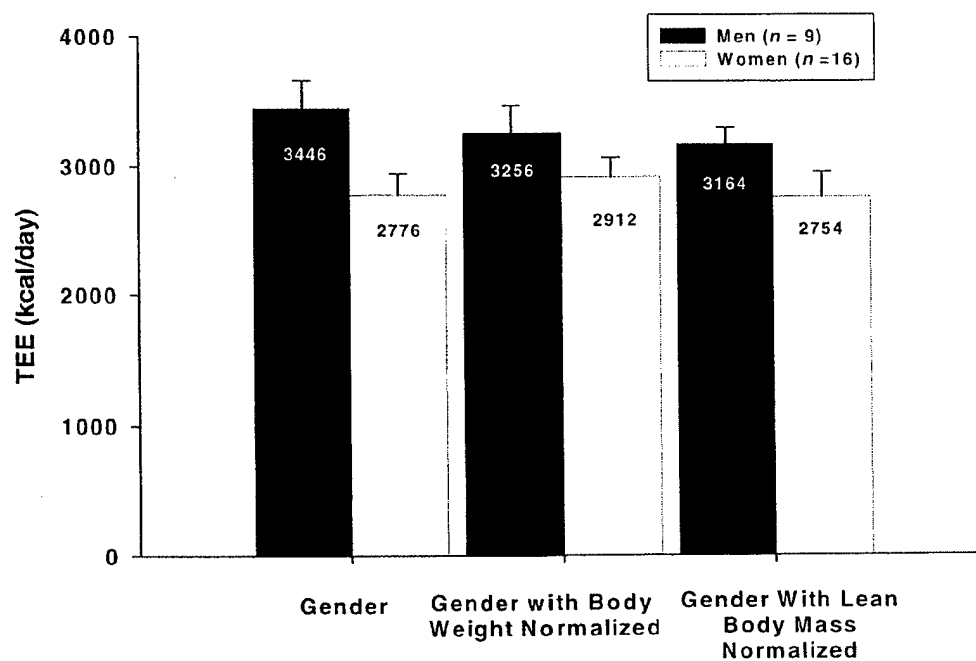Figure 2. Total energy expenditure (TEE) (mean ± SEM) by gender assessed using doubly labeled water.

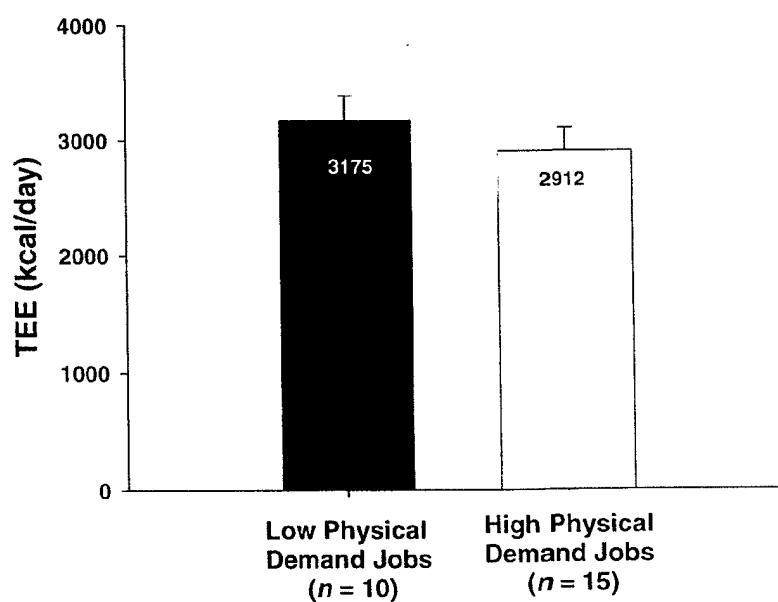Figure 3. Total energy expenditure (TEE) (mean ± SEM) by job type assessed using doubly labeled water.

Table 2. Activity and type (mean ± SEM) with proportion of totals by gender.

	Men (n = 7)	% of Total	Women (n =10)	% of Total	Significance
Activity (Hrs)[1]	91 ± 11	52	104 ± 15	58	NS
Total Hours Assessed	176 ± 9	—	181 ± 4	—	NS
Types of Steps (Number of)					
Other Slow Movements	16,832 ± 4740	55	16,704 ± 1464	52	NS
Walking	11,862 ± 3823	38	13,594 ± 1845	43	NS
Running	2404 ± 2403	7	1657 ± 520	5	NS
Total Steps	31,093 ± 8434	100	33,628 ± 3429	100	NS

[1] "No Activity" includes sleeping and when awake with no movement of the foot.

Table 3. Activity and type (mean ± SEM) with proportion of totals by job type.

	High Physical Demand Jobs (n = 10)	% of Total	Low Physical Demand Jobs (n = 7)	% of Total	Significance
Activity (Hrs)[1]	107 ± 13	58	86 ± 11	51	0.04
Total Hours Assessed	186 ± 14	—	167 ± 12	—	NS
Types of Steps (Number of)					
Other Slow Movements	19,597 ± 2496	52	11,543 ± 2496	52	0.05
Walking	16,059 ± 2626	43	9329 ± 3150	42	NS
Running	1755 ± 577	5	1217 ± 553	6	NS
Total Steps	37,411 ± 4878	100	22,113 ± 5481	100	0.05

[1] "No Activity" includes sleeping and when awake with no movement of the foot.

Figure 4. Total energy expenditure (TEE) ($n = 17$) assessed using doubly labeled water (DLW) vs. that predicted from pedometry.
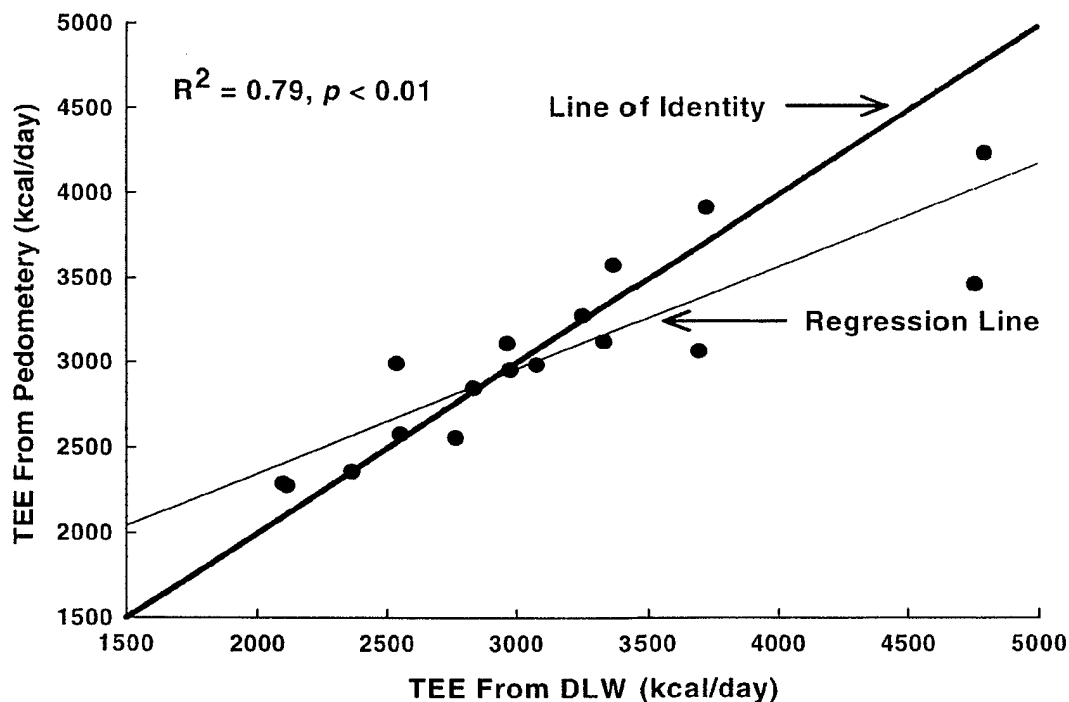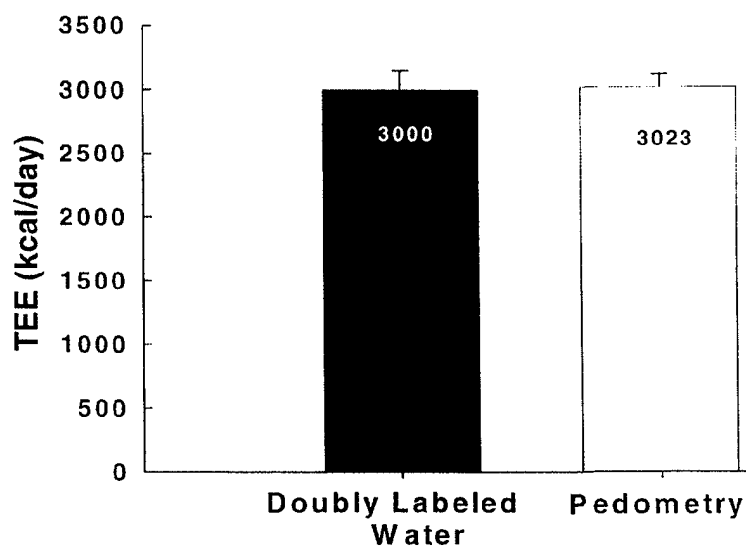

Figure 5. Total energy expenditure (TEE) ($n = 17$; mean $\pm$ SEM) assessed by doubly labeled water and predicted from pedometry.

DISCUSSION

Total energy expenditure estimates were calculated using an algorithm that partitioned pedometry data according to the exercise intensity and integrated estimated resting metabolism, an important component of overall TEE, into the equation. To assess the reliability of pedometer predicted TEE, the pedometer-generated estimates of TEE were compared to those determined by DLW (the scientific community's gold standard of free-living TEE measurement). Volunteers in the present study engaged in many forms of activity classified by the pedometers into one of four categories (run, walk, other slow movements, and no activity), 24 hours a day for 8 days. The use of this pedometer and the associated algorithm significantly predicted TEE in U.S. Navy sailors living and working aboard ship. While this pedometer method significantly predicted the group mean within acceptable limits ($\pm$ 23 kcal/day), individual prediction of TEE was not as accurate.

The mean 23 kcal/day difference predicted by pedometers was well within the $\pm$ 193 kcal/day 95% confidence interval established. Total energy expenditure predicted by pedometry was on average within 1% of DLW assessed TEE. This compared favorably with that of the physical activity monitor worn in chest pockets by Hot Shot firefighters (Manufacturing Technology, Inc., Fort Walton Beach, FL) that predicted TEE within 3% of that assessed by DLW (8,17). Applying the concept of determining different rates of energy expenditure and the proportion of time spent at each exercise intensity (15) may have been a determining factor of the improved predictability of these pedometers and the associated algorithm compared to previous comparisons of pedometer predicted TEE (6,7,12).

The use of these pedometers and the developed algorithm is not suitable for predicting individual TEEs. Examination of the differences in line slopes between the regression line and the line of identity illustrates the problem with predicting some of the individual TEEs. Especially problematic are those values above 4000 kcal/day. For example, the two sailors with the highest energy expenditures of 4796 kcal/day and 4580 kcal/day (from DLW) had pedometer predicted values of only 4242 kcal/day and 3467 kcal/day respectively. These data illustrate that upper levels of TEE are under-predicted by this pedometry method. Not as problematic, but still an issue are TEEs of less than 2500 kcal/day, where the pedometry method tends to over-predict TEE. Compared to many other military warfighters (22), TEE in these sailors was relatively modest. Thus, the under-prediction may become even more problematic as TEE increases. However, it is also possible those who had TEEs over 4000 kcal/day, expended energy in non-locomotive ways such as repetitive heavy lifting, a possibility of those confined to shipboard duty. Secondly, the unique environment of the ship with the abundance of ramps and ladders, may have limited the ability to generalize this method to other warfighters with land-based missions, which are more common. Future studies should test this method on warfighters whose TEE exceeds 4000 kcal/day to ensure validity of measurement in the range of energy expenditure of most combat warfighters (22).

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One possible explanation for the under-prediction at the higher levels of EE could have been the way the data was captured and saved by the pedometers. The data was saved in as short as 1-second intervals providing accurate detail in amount of time spent in each activity. However, when the movement did not change rapidly, the data was saved in as long as 30-minute intervals (Table 4). Over the course of an 8-day study, small errors of not accurately determining precisely when the exercise changed from inactive to active could have multiplied, producing inaccuracies in the prediction model for individuals. The inaccuracies would be more pronounced in those individuals with greater exercise intensities and for those who had more changes in activity levels. Furthermore, analyzing the data files to determine the proportion of time spent in each activity became a very time-consuming and laborious task. Future versions of these pedometers should use the internal clock of the pedometer to calculate the proportion of time spent in each mode of activity, permitting more accurate data and more efficient calculation of EE from the various modes of activity.

Table 4. Example of a portion of a data file from the AMS-2 foot-ground contact pedometer (Fitsense Technology, Inc., Wellesley, MA).

Date	Time	Type of Activity	Date	Time	Type of Activity
24	0:09:48	Slow	24	5:39:10	NoAct
24	0:09:49	Slow	24	6:09:03	NoAct
24	0:39:03	NoAct	24	6:39:07	NoAct
24	1:09:07	NoAct	24	7:09:00	NoAct
24	1:39:00	NoAct	24	7:39:04	NoAct
24	2:09:04	NoAct	24	8:09:08	NoAct
24	2:39:08	NoAct	24	8:39:01	NoAct
24	3:09:01	NoAct	24	9:09:05	NoAct
24	3:39:05	NoAct	24	9:39:09	NoAct
24	4:09:09	NoAct	24	9:43:06	Slow
24	4:39:02	NoAct	24	9:46:14	Slow
24	5:09:06	NoAct	24	9:47:47	Slow

Total energy expenditure of female sailors were less than those of male sailors doing comparable jobs because they had a smaller body mass and lower RMR. Total energy expenditure of the female sailors were similar to those of female U.S. Army soldiers participating in a field hospital FTX (3), while the male sailors' TEE were similar to U.S. Army soldiers doing field training in a temperate environment (4). There were no differences in TEE by job classification. One hypothesis for this finding is that those with low physical demand jobs did more recreational physical activity than those with high physical demand jobs. However, a more plausible explanation may be that TEE was not related to this job classification (16,24). Since the job classifications were based on subject matter experts' evaluations of the necessary strength, flexibility, body balance, and stamina characteristics to complete a job it is not surprising that the classifications were unrelated to energy requirements. Many of the high physical

demand jobs may have required high levels of strength or skill but were not particularly arduous in nature, therefore, the amount of work did not exceed jobs with lower physical demands. Based on these results, physical demand classifications do not help predict the energy requirements of Navy jobs.

In conclusion, group averages of TEE were significantly predicted by the use of pedometers in the range of 3000 kcal/day. Unacceptable errors existed for the use of pedometers to predict individual TEE. Furthermore, TEE errors were most problematic in those with TEEs over 4000 kcal/day. This problem could potentially impact even group estimates for those with TEEs over 4000 kcal/day. Previous attempts at validating free-living pedometer predicted TEEs with DLW have been performed with elderly patients (7), overweight women (6), and young healthy women (12). All of these groups, including the sailors in the present study, expend much less energy than most combat military personnel (22). Since TEE associated with various military operations are not entirely known, and the daily minute-to-minute pattern of EE in military operational training is not known, further work on pedometry appears justified.

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